Effects of Group Selection for Productivity and Longevity on Blood Concentrations of Serotonin, Catecholamines, and Corticosterone of Laying Hens

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ABSTRACT Selection of a line of White Leghorn chickens for high group productivity and longevity resulted in reducing cannibalism and flightiness in multiple-hen cages. Improvements in survival might have been due to changes of physiological homeostasis. The objective of the present study was to test the hypothesis that genetic selection for high (HGPS) and low (LGPS) group productivity and survivability also altered regulation of neuroendocrine homeostasis. Hens were randomly assigned to individual cages at 17 wk of age. At 21 wk of age, blood concentrations of dopamine, epinephrine, norepinephrine, and serotonin were measured using HPLC assay. Blood concentrations of corticosterone were measured using radioimmunoassay.

The LGPS hens had greater blood concentrations of dopamine and epinephrine than the HGPS hens ($P < 0.01$). The blood concentration of norepinephrine was not significantly different between the lines, but the ratio of epinephrine to norepinephrine was greater in the LGPS hens ($P < 0.01$). The blood concentrations of serotonin were also higher in the LGPS hens compared to those in the HGPS hens ($P < 0.01$). Although the HGPS hens tended to have a higher level of blood corticosterone, the difference was not significant (1.87 ± 0.19 vs. 1.49 ± 0.21 ng/mL; $P = 0.08$). The results suggest that selection for group productivity and survivability alters the chickens' neuroendocrine homeostasis, and these changes may correlate with its line-unique coping ability to domestic environments and survivability.

(*Key words*: group selection, serotonin, catecholamine, corticosterone, well-being)

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INTRODUCTION

Genes determine functions of the neuroendocrine system in controling animal coping strategies and productivities. Selection for phenotypic characteristics associated with specific physiological or behavioral displays, including domestic behavior and reproductive performances, has become a major tool for studying functions of animal neuroendocrine systems and to improve animal well-being (Tecott and Barondes, 1996; Siegel and Dunnington, 1997; Muir and Craig, 1998; Georges, 1999; Kappes, 1999; Koolhaas et al., 1999).

Effects of selection on behavioral adaptation and productivity have been implicated in functional alterations of the neuroendocrine system in controling the release of endogenous psychotropic compounds, such as serotonin (5-HT), catecholamines [dopamine (DA), epinephrine (EP) and norepinephrine (NE)], and corticosterone (CORT) (Dohms and Metz, 1991; Castanon et al., 1995; Siegel et al., 1999). Disregulation of these biogenic amines, hormones, including their concentrations and metabolites as well as densities of their receptors, has been associated with abnormal behaviors (Valzelli, 1984; Bell and Hobson, 1994; Popova et al., 1997; Berman and Coccaro, 1998) and altered reproduction (Sharp et al., 1984; Tuomisto and Mannisto, 1985; Barraclough, 1992; Sirotkin and Schaeffer, 1997). Previous studies in rodents have shown that alterations of the neuroendocrine homeostasis can result from reorganization of the brain structure and function in adaptation to a given environment (de Kloet et al., 1996; Ferris, 2000), which in turn affects an animal's ability to cope and its well-being. There is evidence that the function of the avian neuroendocrine system in response to stimulation is analogous to that in rodents (Harvey et al., 1984).

Several species of poultry have been genetically selected for differences in behavioral response to stressors

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Abbreviation Key: CORT = corticosterone; DA = dopamine; EP = epinephrine; HGPS = hens with high group productivity and survivability; H:L = heterophils:lymphocytes; LGPS = hens with low group productivity and survivability; NE = norepinephrine; 5-HT = serotonin.

such as open-field exposure (Jones et al., 1992), physical and manual restraint (Mills and Faure, 1991; Jones and Satterlee, 1996), and fear of humans (Jones et al., 1994). Stress-induced avian behavioral sensitivity is based on changes in the neuroendocrine system, including alternative adrenal functions (Brown and Nestor, 1974) and plasma concentrations of CORT (Thompson et al., 1980). In addition, previous studies have demonstrated that there are hereditable associations between release of hormones and display of physical indexes, such as growth rate, egg production, and semen yield (Bayyari et al., 1997; Nestor et al., 2000). Collectively, these studies are consistent with the hypothesis that the genotype and phenotype of an animal influence its neuroendocrine reactivation to stimulations, which in turn alters the animal's behavioral adaptability and well-being (Lamont, 1994; Siegel, 1995; Mench and Duncan, 1998). Understanding the interrelations among genetic factors, domestic behaviors, and neuroendocrine homeostasis in chickens is critical in preventing harmful behaviors and enhancing productivity associated with welfare problems in the poultry industry (Mench, 1992; Craig and Swanson, 1994; Muir and Craig, 1998).

A line of White Leghorns chickens was developed at Purdue University (Muir, 1996; Craig and Muir, 1996a,b; Muir and Craig, 1998) using a genetic selection program termed "group selection" that emphasized group productivity and survivability of families housed in colony cages. Group productivity was based on average rate of lay, and longevity was based on average days of survival up to 60 or 72 wk of age. Chickens were not beak-trimmed and were kept 12 hens per cage in cages illumined at high intensity. The positively selected line (HGPS; previously termed KGB, Kinder and Gentler Bird) has been shown to have improved rate of lay, survival, and feather score as well as reduced cannibalism and flightiness as compared to the nonselected control base population from which the line was developed (Craig and Muir, 1996a,b). Compared to control and commercial lines, the HGPS line also had better and faster adaptation to various stressors such as social, handling, cold, and heat (termed selection line, Hester et al., 1996a,b,c). The reverse-selected hens (LGPS line) were selected for the lowest group productivity and shortest survivability resulting from cannibalism (Cheng et al. 2001). The HGPS hens exhibited greater cell mediated immunity, whereas the LGPS hens had heterophilia and a greater heterophil to lymphocyte ratio (Cheng et al., 2001). Collectively, genetic selection has created lines with significantly different phenotypes, each of which has unique characteristics in physical indexes, domestic behavior, responsiveness to stressors, and immunity, which could be reflected in differing capacity to regulate the neuroendocrine system; however, the hypothesis has not been tested. The objective of the present experiment was to determine the effect of genetic selection on concentrations of 5-HT, DA, EP, NE, and CORT and to evaluate how these changes are related to the well-being of the chicken in response to stress.

MATERIAL AND METHODS

Development of the Genetic Lines

The first seven generations of selection for the HGPS line was previously reported by Muir (1996). The eighth generation was produced from mating 1,248 hens with 312 roosters selected at random from 20-wk-old pullets and roosters of the seventh generation. Eggs were collected and hatched as described previously (Muir, 1996). At 18 wk of age, 9,216 pullets were housed by half-sib family in 768 12-hen cages, which was the base population and was used as a control line in the study. After 52 wk of production (72 wk of age), hens from 12 cages with the highest group productivity (egg number) and the lowest mortality from cannibalism and flightiness, along with their full- and half-sib brothers, were selected for the HGPS line. To establish a comparison line, hens from 12 cages with the lowest group productivity and the highest mortality, along with their full- and half-sib brothers, were used to establish a reverse selected LGPS line.

Hens were randomly mated within each line, four hens per rooster, avoiding full or half-sib mating, to reproduce the ninth generation of the HGPS and the LGPS lines that was used as the genetic material for this research. The details of the selection technology and rearing program have been reported previously (Muir, 1996). Pullets of each genetic line were not-beak trimmed. They were reared under the same conditions, hatched, vaccinated against Marek's and Newcastle disease, and maintained using standard management practices in raised wire cages up to 17 wk of age. At 17 wk of age, hens from each line were randomly assigned to single-hen cages, each providing 1,085 cm^2 per hen. Feed and water were provided ad libitum. Overhead lights were on daily from 0700 until 1900 h initially and were increased by 15 min/wk. Light duration was at 13 h daily when the study was performed.

Chicken care guidelines were in strict accordance with the rules and regulations set by Federation of Animal Science Societies (Craig et al., 1999). Experimental protocols were approved by the institutional Animal Care and Use Committee at Purdue University. Efforts were made to minimize animal suffering and the number of animals used.

Blood Sampling

Based on previous observations, the main behavioral adaptation of the HGPS hens in responses to social stress became stable after the first 3 wk (Craig and Muir, 1996a,b). At 21 wk of age, 12 replicates of 24 hens from the HGPS and LGPS lines, without a plumped egg confirmed by palpating, were bled between 0900 and 1000 h (Savory and Mann, 1997). A 5-mL blood sample was collected into a heparinized tube from the brachial vein of each hen within 2 min of removal from its cage. Whole blood was used to measure concentrations of 5-HT. For measuring concentrations of catecholamines and CORT, blood samples were centrifuged at 700 × g for 15 min at 20 C. Plasma was kept on ice for further processing or kept at –80 C until measurement.

HPLC Assay

To measure blood concentrations of catecholamines, a plasma catecholamine analysis kit[2] was used. Duplicate plasma samples were acidified with 4 *M* perchloric acid, followed by deproteinization with the supplied reagent. After centrifugation, the acid supernatants with internal standard dihydrocybenzylamine were added and absorbed onto an alumina minicolumn to bind the catecholamines. HPLC columns were then rinsed and eluted with the supplied solutions. Following injection of eluents into the reverse-phase columns, catechols were detected by liquid chromatography with electrochemical detection. The mobile phase flowed rate was 1.3 mL/min. The concentrations of DA, EP, and NE were calculated from a reference curve made using supplied standards.

To measure blood concentration of 5-HT, whole blood samples were acidified in duplicate using 4 *M* perchloric acid and freshly prepared 3% ascorbic acid. After centrifugation, the acid supernatants were injected onto the columns. The mobile phase flow rate was 1.0 mL/min., and the concentration of 5-HT was calculated from a reference curve made using standard 5-HT.

Radioimmunoassay

Total plasma CORT was measured in triplicate using a commercial ^{125}I CORT radioimmunoassay kit[3] with a modification based on company suggestion for use in chicken samples. To validate parallelism and recovery in chickens, adjustments of dilution to 1 to 5, were made, i.e., 20-μL sample to 80-μL steroid diluent. The concentration of CORT was calculated from a reference curve that ranged from 0.1 ng/mL (95.4% binding) to 4.0 ng/mL (14.9% binding), and the correlation coefficient was 0.9995. Recovery of exogenous CORT was determined by adding known amounts of unlabeled CORT to aliquots steroid diluent to produce theoretical concentrations of 0.5, 1.0, and 2.0 ng/mL and to result in recovered concentrations of 0.48, 1.08, and 1.97 ng/mL, respectively. The sensitivity of the assay was 0.02 ng/mL. All samples within the experiment were analyzed at same time. Within- and between-assay coefficients of variation were 7.6% and 9.8%, respectively.

Statistical Analysis

The experimental design was a completely randomized with genetic lines as the main effect and cages as the experimental unit. Differences between lines were determined using a single degree of freedom F-test.

[2]ESA, Inc., Chelmsford, MA 01824.

[3]INC Biomedicals, Inc., Costa Mesa, CA 92626.

TABLE 1. Genetic selection-induced alterations in the productivity and survivability in hens

Trait	HGPS line[1]	LGPS line
Mortality, %	$1.3^b \pm 0.1$	$8.6^a \pm 0.5$
Longevity, d	$363^b \pm 0.4$	$193^a \pm 21$
Egg number, per hen	$295^b \pm 11$	$108^a \pm 12$
Egg mass, per hen, g/d	$48^b \pm 2$	$17^a \pm 1.8$
Egg weight, g	59.4 ± 0.6	58.9 ± 0.8

[a,b]Means within a row with no common superscript differ significantly ($P < 0.05$).

[1]The HGPS and LGPS lines were selected from high and low productivity and survivability, respectively, resulting from cannibalism and flightiness.

RESULTS AND DISCUSSION

Line differences in blood concentrations of 5-HT, DA, and EP were found (Tables 2 and 3), which provided evidence that genetic selection for group productivity and survivability with reduced cannibalism and flightiness results in alterations in the regulation of the neuroendocrine system. The data are consistent with previous findings that domestication of animals is associated with hereditary reorganization of the neuroendocrine system (Naumenko et al., 1987; de Kloet et al., 1996; Ferris, 2000) and changes in neurochemical homeostasis (Bilzard et al., 1983; Balaban et al., 1996; Crusio, 1996; Davidson et al., 2000; Oquendo and Mann, 2000). These changes in the neuroendocrine functions were also associated with the line's unique productivity and survivability (Table 1).

Associations of Line Differences in Physical Indexes and Blood Concentration of Catecholamines

Dopamine. Dopamine is involved in controling domestic behaviors (Bell and Hepper, 1987; Haller et al., 1997; Kuikka et al., 1998) and regulation of productivity (Sotowska-Brochocka et al., 1994). Abnormalities of blood and brain DA systems are associated with disfunctional behavior as well as with a decline in ability to cope with stress (Driscoll et al., 1998; Kuikka et al., 1998). In agreement with these findings, the HGPS hens, selected for high survivability with reduced cannibalism and flightiness, had a significantly less blood DA (Table 2) and better and quicker adaptation to various stressors (Hester et al., 1996a,b). In addition, the lower blood DA in the HGPS hens was also associated with sedate and passive behaviors (Craig and Muir, 1996b). In contrast, The LGPS hens had greater blood DA concentrations (Table 2), which could be linked to the specific reorganization of behaviors such as cannibalism, resulting in higher mortality (Table 1).

The present findings are consistent with heritable variation of DA concentrations reflected in individual coping strategies (Benus et al., 1991; Vogel and Harris, 1991; Driscoll et al., 1998). Similar to the present findings, higher concentrations of DA were also found in the brains of Japanese quail with aggressive behavior (Edens, 1987) and were in the selected brain regions of humans and rodents following aggressive or defensive activities (Lewis et al., 1994; Miczek et al., 1994; Kuikka et al., 1998; Mersmann, 1998). Increased DA activity was also found in Roman rats selected for high avoidance, but not in their counterparts, associated with increased locomotor activities, a marker of anxiety and stressful status (Corda et al., 1997). Based on the present and previous observations, the selection-induced differences in dopaminergic and survivability could be interpreted as evidence that coping strategies of the selected breeds are based on inheritance pattern and phenotypic correlations of behavioral, physiological, and neuroendocrine variables (Castanon et al., 1995). In the present strains selection may directly or indirectly influence regulation of the dopaminergic system and, in turn, activation of the DA system to favor survival behavior in the HGPS hens.

Greater blood concentrations of DA in the LGPS hens with lower productivity (Table 1 and 2) are consistent with the hypothesis that the dopaminergic system is one of the main inhibitory neuronal systems that controls development of the reproductive systems (Becu-Villalobos and Libertun, 1995) and productivity (Sotowska-Brochocka et al., 1994). Although identification of mechanisms that underlie the inhibitory effects of DA on productivity in the present lines is unclear, previous research findings suggest that regulation might be related to genetic selection-induced changes in physiological functions of the neuroendocrine system, including the hypothalamic-pituitary-adrenal (HPA) and hypothalamic-pituitary-gonadal (HPG) axes. For example, endogenous DA secreted in the hypothalamus exhibits tonic inhibition of the secretion of luteinizing hormone-releasing hormone (Contijoch et al., 1992) and luteinizing hormone (Martin et al., 1981). Whether or not there are similar functions of DA in regulating reproduction in the present lines is unclear. Our results suggest that group selection for productivity between the HGPS and LGPS lines also alters functions of the dopaminergic system.

Epinephrine and Norepinephrine, As “stress hormones,” both EP and NE participate in many physiologic and pathologic processes, including regulation of emotion and motivation in response to stimulations. Changes in EP and NE levels, as well as the ratio of EP:NE have been used as indicators of the “organisms” well-being and ability to cope with stress (Goldstein, 1981; Dillon et al., 1992). Consistent with this hypothesis, the present study showed that the changes in blood concentrations of EP and ratio of EP:NE between the HGPS and LGPS hens were correlated with differences in productivity and mortality from cannibalism and flightiness (Tables 1 and 2). The major factor causing a greater EP:EN ratio in LGPS hens was higher concentrations of EP, as there was no significant difference in the concentration of NE between the lines (Table 2). A similar upregulation of EP concentration was found in turkeys that were selected for higher adrenal response to cold stress (Brown and Nestor, 1974). Turkeys of that line also, similar to the LGPS hens, laid significantly fewer eggs, were hyperactive, and had poorer feed efficiency. These data support the hypothesis that phenotypic variation of concentrations of EP and EP:NE ratio, in response to selection, may reflect individual coping strategies that control changes in an animal’s behavioral patterns.

Associations of Line Differences in Physical Indexes and Blood Concentrations of Serotonin

The role of serotonin is to modulate behavioral and physiological processes, including feeding, sexual, and behavioral (Jernej and Cicin-Sain, 1990; Cook and Leventhal, 1996; Olivier et al., 1998). Abnormalities of blood and brain 5-HT and its metabolite 5-hydroxyindoleasetic acid, as well as the density of its receptors, have been used as major indicators to evaluate alterations in behavioral adaptability and reproduction (Bell and Hobson 1994; Popova et al., 1997; Maswood et al., 1998).

In the central nervous system, 5-HT functions to inhibit aggression, thereby controling domestic behavior (Popova et al., 1975). Depletion or decrease of 5-HT concentrations and the ratio of 5-hydroxyindoleasetic acid:5-HT have been implicated in dysfunctional behaviors, including aggressiveness and violence in humans and animals (Higley et al., 1996; Unis et al., 1997; Parmigiani et al., 1999; Popova et al., 1999) and cannibalism in rats (Barofsky et al., 1983).

In the peripheral system, however, biological roles of 5-HT in behavioral adaptation and motivational regulation are unclear. Decreased, increased, and unchanged blood 5-HT concentrations have been found in association with behavioral dysfunctions, including aggressiveness (Hanna et al., 1995; Moffitt et al., 1998). The conflicting data from different investigations could be related to different genetic selection programs, species, behavioral evaluations, and stressors used as well as duration and

TABLE 2. Genetic selection-induced alterations in blood concentrations of catecholamines in hens

Group[1]	Dopamine (ng/mL)	Epinephrine (EP) (ng/mL)	Norepinephrine (NE) (ng/mL)	EP:NE (%)
HGPS	0.59 ± 0.08^a	0.30 ± 0.06^a	0.86 ± 0.12	34.0^a
LGPS	2.42 ± 0.76^b	0.59 ± 0.13^b	0.84 ± 0.13	72.5^b
HGPS:LGPS	24.4%	50.8%	102.3%	46.9%

[a,b]Means within a column with different superscript are statistically different ($P < 0.01$).

[1]The HGPS and LGPS lines were selected from high and low productivity and survivability, respectively, resulting from cannibalism and flightiness.

frequency of stressor presentation. The present data showed that higher blood 5-HT levels were associated with lower survivability resulting from higher cannibalism in the LGPS hens (Table 1 and 2). Similar correlations, i.e., positive associations of blood 5-HT levels and aggressiveness, were also found in adolescents with behavioral conduct disorder (Cook and Leventhal, 1996; Unis et al., 1997) and in dominant male monkeys (Steklis et al., 1986; Raleigh et al., 1991). Values of blood 5-HT have been used as a heritably stable biological parameter in rodents (Jernej and Cicin-Sain, 1990). However, in poultry, further studies are needed to evaluate whether blood concentration of 5-HT could serve as a biological trait marker for domestic behaviors.

Whether higher concentrations of 5-HT in blood in the LGPS line represent the same changes of 5-HT occurring in the brain is unclear, as 5-HT cannot pass the brain-blood barrier (Pietraszek et al., 1992) and is regulated differently in the central nervous system and peripheral tissues (Popova et al., 1978; Lampugnani et al., 1986; Pietraszek et al., 1992). Although previous studies have shown that supplemental tryptophan, a precursor of 5-HT, decreases aggression in feed-restricted male chickens (Shea et al., 1991), the effect of tryptophan on modification of aggression was related to centrally enhanced neuronal firing rather than a peripheral increase 5-HT resulting from conversion of tryptophan (Shea et al., 1990). Steklis et al. (1986) also found that, in dominant monkeys, even though they had higher concentrations of blood 5-HT, a deletion of central 5-HT was found, which was associated with their aggressive behaviors. Although a similar correlation of selection-induced different changes of 5-HT systems between the CNS and periphery could have occurred in the LGPS hens, further studies are needed to determine whether different regulations of the peripheral and central nervous systems are present in these lines.

The finding that the LGPS hens, compared to the HGPS hens, had higher concentrations of circulating 5-HT but lower productivity (Table 1 and 2) is consistent with the reports that 5-HT has a tonic, inhibitory effect on sexual behavior and reproduction (Sirotkin and Schaeffer, 1997), such as inhibition of luteinizing hormone secretion and ovulation (Nagatsuka, 1983; Morello et al., 1992; Lorrain et al., 1998). The effects of 5-HT on sexual behavior were positively correlated to stimulation of the pre-optic area and median eminence of the hypothalamus (Gonzalez et al., 1997) and were differentially regulated by 5-HT receptors (Wilson and Hunter, 1985) in rodents. At present, the cellular mechanisms that genetically regulate productivity between the selected lines are unclear; however, they may be the same mechanisms as those found in rodents. There is evidence that the functions of the avian neuroendocrine system that control stimulators are analogous to those in rodents (Harvey et al., 1984). In addition, there are similar distributions of neurotransmitter receptors, including 5-HT receptors, in avian and mammals (Richfield et al., 1987; Walker et al., 1991).

TABLE 3. Genetic selection-induced alterations in blood concentrations of serotonin and corticosterone in hens

Group[1]	Serotonin (ng/mL)	Corticosterone (ng/mL)
HGPS	11.8 ± 0.07[a]	1.87 ± 0.19
LGPS	14.3 ± 0.06[b]	1.49 ± 0.21
HGPS:LGPS	82.5%	126%

[a,b]Means within a column with different superscript are statistically different ($P < 0.01$).

[1]The HGPS and LGPS lines were selected from high and low productivity and survivability, respectively, resulting from cannibalism and flightiness.

Associations of Line Differences in Physical Indexes and Blood Concentrations of Corticosterone

Corticosterone, as one of the "stress hormones," has multifunctional roles in normal and abnormal states, including regulation of an organism's behavioral patterns, coping styles, and well-being (Savory and Mann, 1997; Haller et al., 2000).

The concentrations of CORT in the HGPS hens were not significantly higher than those of the reverse-selected line (Table 3; 1.87 vs. 1.49 ng/mL; $P = 0.08$). The lack of an effect of selection on blood concentrations of CORT in the present chicken strains could be due to heritable acclimation, as the strains were originally selected from the colony caged under continuous exposure to social stress, or to maintenance of chickens at nonstressful single-hen cages. Similarly, Hester et al. (1996b) found no significant difference between the selected and control lines on plasma CORT concentrations in response to acute heat stress, which may be related to acclimation caused by prior repeated stress, including social, cold, and fear stress. In addition, other researchers have shown that prolonged or repeated exposures to stressors could lead to decreased adrenal responsiveness, reduce the mass of the adrenals, and decrease CORT secretion, even though they initially produced great increases in plasma CORT (Gross and Siegel, 1979; Siegel and Gould, 1982; Jones et al., 1998). In a review of previous studies, Siegel (1995) suggested that concentrations of CORT may be better indicators of acute or life-threatening stress and that end-organ responses such as heterophils:lymphocytes (H:L) ratios may be better indicators of chronic stress. In agreement with this hypothesis, our present and previous results (Cheng et al., 2001) showed an effect of selection on circulating heterophils and H:L ratios with no effect on CORT in the selected lines, as the LGPS hens had heterophilia and a greater ratio of H:L.

The differences in blood concentrations of 5-HT, DA, and EP in the present strains may be due to housing chickens in single-hen cages, as they were selected on a multiple-hen condition, and isolation has been determined to be a stressor. However, it is unlikely in the present study, because the hens were not completely separated from each other, as they not only could see but also could touch each other through the wire cages. Furthermore, previous studies with single-hen vs. multiple-hen cages have shown that there was no difference in the H:L ratio in the selected line (Hester et al., 1996b). The H:L ratio has been used as an indicator of stress status in chickens (Gross and Siegel, 1983; Beuving et al., 1989; Maxwell, 1993).

In conclusion, the present study demonstrates that genetic selection for high and low group productivity and longevity with alterations in cannibalism and flightiness affected the regulations of the neuroendocrine system. There were line differences for blood concentrations of 5-HT, DA, and EP. The present findings further support the hypothesis that changes in domestic animal behaviors and productive performances resulting from selective breeding likely reflect changes in the link between the nervous and endocrine systems. The unique homeostatic characteristics of each selected line may provide a neurobiological basis for investigating effects of genetic factors on physiological functions of biogenic amines involved in productivity and longevity as related to domestic behavior.

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REFERENCES

Balaban, E., J. S. Alper, and Y. L. Kasamon, 1996. Mean genes and the biology of aggression: a critical review of recent animal and human research. J. Neurogenet. 11:1–43.

Barofsky, A. L., J. Taylor, Y. Tizabi, R. Kumar, and K. Jones-Quartey, 1983. Specific neurotoxin lesions of median raphe serotonergic neurons disrupt maternal behavior in the lactating rat. Endocrinology 113:1884–1893.

Barraclough, C. A., 1992. Neural control of the synthesis and release of luteinizing hormone-releasing hormone. Ciba. Found. Symp. 168:233–246.

Bayyari, G. R., W. E. Huff, N. C. Rath, J. M. Balog, L. A. Newberry, J. D. Villines, J. K. Skeeles, N. B. Anthony, and K. E. Nestor, 1997. Effect of the genetic selection of turkeys for increased body weight and egg production on immune and physiological responses. Poultry Sci. 76:289–296.

Beuving, G., R. B. Jones, and H. J. Blokhuis, 1989. Adrenocortical and heterophil/lymphocyte responses to challenge in hens showing short or long tonic immobility reactions. Br. Poult. Sci. 30:175–184.

Becu-Villalobos, D., and C. Libertun, 1995. Development of gonadotropin-releasing hormone (GnRH) neuron regulation in the female rat. Cell. Mol. Neurobiol. 15:165–176.

Bell, R., and P. G. Hepper, 1987. Catecholamines and aggression in animals. Behav. Brain Res. 23:1–21.

Bell, R., and H. Hobson, 1994. 5-HT1A receptor influences on rodent social and agonistic behavior: a review and empirical study. Neurosci. Biobehav. Rev. 18:325–338.

Benus, R. F., B. Bohus, J. M. Koolhaas, and G. A. van Oortmerssen, 1991. Heritable variation for aggression as a reflection of individual coping strategies. Experientia 47:1008–1019.

Berman, M. E., and E. F. Coccaro, 1998. Neurobiologic correlates of violence: relevance to criminal responsibility. Behav. Sci. Law. 16:303–318.

Bilzard, D. A., L. S. Freedman, and B. Liang, 1983. Genetic variation, chronic stress, and the central and peripheral noradrenergic system. Am. J. Physiol. 245:R600–605.

Brown, K. I., and K. E. Nestor, 1974. Implications of selection for high and low adrenal response to stress. Poultry Sci. 53:1297–1306.

Castanon, N., F. Perez-Diaz, and P. Mormede, 1995. Genetic analysis of the relationships between behavioral and neuroendocrine traits in Roman high and low avoidance rat lines. Behav. Genet. 25:371–384.

Cheng, H. W., S. D. Eicher, Y. Chen, P. Singleton, and W. M. Muir, 2001. Effect of genetic selection for group productivity and longevity on immunological and hematological parameters of chickens. Poultry Sci 80:1079–1086.

Contijoch, A. M., C. Gonzalez, H. N. Singh, S. Malamed, S. Troncoso, and J. P. Advis, 1992. Dopaminergic regulation of luteinizing hormone-releasing hormone release at the median eminence level: immunocytochemical and physiological evidence in hens. Neuroendocrinology 55:290–300.

Cook, E. H., and B. L. Leventhal, 1996. The serotonin system in autism. Curr. Opin. Pediatr. 8:348–354.

Corda, M. G., D. Lecca, G. Piras, G. Di Chiara, and O. Giorgi, 1997. Biochemical parameters of dopaminergic and GABAergic neurotransmission in the CNS of Roman high-avoidance and Roman low-avoidance rats. Behav. Genet. 27:527–536.

Craig, J. V., W. F. Dean, G. B. Havenstein, K. K. Kruger, K. E. Nestor, G. H. Purchase, P. B. Siegel and G. L. van Wicklen. 1999. Guidelines for poultry husbandry, Pages 55–66. *in*: Guide for the Care and Use of Agricultural Animals in Agricultural Research and Teaching. Federation of Animal Science Societies. Savoy, IL.

Craig, J. V., and W. M. Muir, 1996a. Group selection for adaptation to multiple-hen cages: beak-related mortality, feathering, and body weight responses. Poultry Sci. 75:294–302.

Craig, J. V., and W. M. Muir, 1996b. Group selection for adaptation to multiple-hen cages: behavioral responses. Poultry Sci. 75:1145–1155.

Craig, J. V., and J. C. Swanson, 1994. Review: welfare perspectives on hens kept for egg production. Poultry Sci. 73:921–938.

Crusio, W. E., 1996. The neurobehavioral genetics of aggression. Behav. Genet. 26:459–461.

Davidson, R. J., K. M. Putnam, and C. L. Larson, 2000. Dysfunction in the neural circuitry of emotion regulation—a possible prelude to violence. Science 289:591–594.

de Kloet, E. R., S. M. Korte, N. Y. Rots, and M. R. Kruk, 1996. Stress hormones, genotype, and brain organization. Implications for aggression. Ann. N. Y. Acad. Sci. 794:179–191.

Dillon, J. E., M. J. Raleigh, M. T. McGuire, D. Bergin-Pollack, and A. Yuwiler, 1992. Plasma catecholamines and social behavior in male vervet monkeys (Cercopithecus aethiops sabaeus). Physiol. Behav. 51:973–977.

Dohms, J. E., and A. Metz, 1991. Stress—mechanisms of immunosuppression. Vet. Immunol. Immunopathol. 30:89–109.

Driscoll, P., R. M. Escorihuela, A. Fernandez-Teruel, O. Giorgi, H. Schwegler, T. Steimer, A. Wiersma, M. G. Corda, J. Flint, J. M. Koolhaas, W. Langhans, P. E. Schulz, J. Siegel, and A. Tobena, 1998. Genetic selection and differential stress responses. The Roman lines/strains of rats. Annu. N.Y. Acad. Sci. 851:501–510.

Edens, F. W., 1987. Agonistic behavior and neurochemistry in grouped Japanese quail. Comp. Biochem. Physiol. A. 86:473–479.

Ferris, C. F., 2000. Adolescent stress and neural plasticity in hamsters: a vasopressin-serotonin model of inappropriate aggressive behaviour. Exp. Physiol. 85:85S–90S.

Georges, M., 1999. Towards marker assisted selection in livestock. Reprod. Nutr. Dev. 39:555–561.

Goldstein, S. D., 1981. Plasma norepinephrine as an indicator of sympathetic neural activity in clinical cardiology. Am. J. Cardiol. 48:1147–1154.

Gonzalez, M. I., P. Greengrass, M. Russell, and C. A. Wilson, 1997. Comparison of serotonin receptor numbers and activity in specific hypothalamic areas of sexually active and inactive female rats. Neuroendocrinology. 66:384–392.

Gross, W. B., and P. B. Siegel, 1979. Adaptation of chickens to their handler, and experimental results. Avian Dis. 23:708–714.

Gross, W. B., and H. S. Siegel, 1983. Evaluation of the heterophil/lymphocyte ratio as a measure of stress in chickens. Avian Dis. 27:972–979.

Haller, J., G. B. Makara, and M. R. Kruk, 1997. Catecholaminergic involvement in the control of aggression: hormones, the peripheral sympathetic, and central noradrenergic systems. Neurosci. Biobehav. Rev. 22:85–97.

Haller, J., S. Millar, J. van de Schraaf, R. E. de Kloet, and M. R. Kruk, 2000. The active phase-related increase in corticosterone and aggression are linked. J. Neuroendocrinol. 12:431–436.

Hanna, G. L., A. Yuwiler, and J. K. Coates, 1995. Whole blood serotonin and disruptive behaviors in juvenile obsessive-compulsive disorder. J. Am. Acad. Child Adolesc. Psychiatry 34:28–35.

Harvey, S., J. G. Phillips, A. Rees, and T. R. Hall, 1984. Stress and adrenal function. J. Exp. Zool. 232:633–645.

Hester, P. Y., W. M. Muir, and J. V. Craig, 1996a. Group selection for adaptation to multiple-hen cages: humoral immune response. Poultry Sci. 75:1315–1320.

Hester, P. Y., W. M. Muir, J. V. Craig, and J. L. Albright, 1996b. Group selection for adaptation to multiple-hen cages: hematology and adrenal function. Poultry Sci. 75:1295–1307.

Hester, P. Y., W. M. Muir, J. V. Craig, and J. L. Albright, 1996c. Group selection for adaptation to multiple-hen cages: production traits during heat and cold exposures. Poultry Sci. 75:1308–1314.

Higley, J. D., S. T. King, M. F. Hasert, M. Champoux, S. J. Suomi, and M. Linnoila, 1996. Stability of interindividual differences in serotoin function and its relationship to severe aggression and competent social behavior in Rhesus macaque females. Neuropsychopharmacology 14:67–76.

Jernej, B., and L. Cicin-Sain, 1990. Platelet serotonin level in rats is under genetic control. Psychiatry Res. 32:167–174.

Jones, B. C., A. Sarrieau, C. L. Reed, M. R. Azar, and P. Mormede, 1998. Contribution of sex and genetics to neuroendocrine adaptation to stress in mice. Psychoneuroendocrinology 23:505–517.

Jones, R. B., A. D. Mills, J. M. Faure, and J. B. Williams, 1994. Restraint, fear, and distress in Japanese quail genetically selected for long or short tonic immobility reactions. Physiol. Behav. 56:529–534.

Jones, R. B., and D. G. Satterlee, 1996. Threat-induced behavioural inhibition in Japanese quail genetically selected for contrasting adrenocortical response to mechanical restraint. Br. Poult. Sci. 37:465–470.

Jones, R. B., D. G. Satterlee, and F. H. Ryder, 1992. Research note: open-field behavior of Japanese quail chicks genetically selected for low or high plasma corticosterone response to immobilization stress. Poultry Sci. 71:1403–1407.

Kappes, S. M., 1999. Utilization of gene mapping information in livestock animals. Theriogenology 51:135–147.

Koolhaas, J. M., S. M. Korte, S. F. De Boer, B. J. Van Der Vegt, C. G. Van Reenen, H. Hopster, I. C. De Jong, M. A. Ruis, and H. J. Blokhuis, 1999. Coping styles in animals: current status in behavior and stress-physiology. Neurosci. Biobehav. Rev. 23:925–935.

Kuikka, J. T., J. Tiihonen, K. A. Bergstrom, J. Karhu, P. Rasanen, and M. Eronen, 1998. Abnormal structure of human striatal dopamine re-uptake sites in habitually violent alcoholic offenders: a fractal analysis. Neurosci. Lett. 253:195–197.

Lamont, S. J., 1994. Poultry immunogenetics: which way do we go? Poultry Sci. 73:1044–1048.

Lampugnani, M. G., W. Buczko, A. Ceci, A. Mennini, and G. de Gaetano, 1986. Normal serotonin uptake by blood platelets and brain synaptosomes but selective impairment of platelet serotonin storage in mice with Chediack-Higashi syndrome. Life Sci. 38:2193–2198.

Lewis, M. H., J. L. Gariepy, P. Gendreau, D. E. Nichols, and R. B. Mailman, 1994. Social reactivity and D1 dopamine receptors: studies in mice selectively bred for high and low levels of aggression. Neuropsychopharmacology 10:115–122.

Lorrain, D. S., L. Matuszewich, and E. M. Hull, 1998. 8-OH-DPAT influences extracellular levels of serotonin and dopamine in the medial preoptic area of male rats. Brain Res. 790:217–223.

Martin, W. H., A. D. Rogol, D. L. Kaiser, and M. O. Thorner, 1981. Dopaminergic mechanisms and luteinizing hormone (LH) secretion. II. Differential effects of dopamine and bromocriptine on LH release in normal women. J. Clin. Endocrinol. Metab. 52:650–656.

Maswood, N., M. Caldarola-Pastuszka, and L. Uphouse, 1998. Functional integration among 5-hydroxytryptamine receptor families in the control of female rat sexual behavior. Brain Res. 802:98–103.

Maxwell, M. H., 1993. Avian blood leucocyte responses to stress. World's Poult. Sci. J. 49:34–43.

Mench, J. A., 1992. Introduction: applied ethology and poultry science. Poultry Sci. 71:631–633.

Mench, J. A., and I. J. Duncan, 1998. Poultry welfare in North America: opportunities and challenges. Poultry Sci. 77:1763–1765.

Mersmann, H. J., 1998. Overview of the effects of beta-adrenergic receptor agonists on animal growth including mechanisms of action. J. Anim. Sci. 76:160–172.

Miczek, K. A., E. Weerts, M. Haney, and J. Tidey, 1994. Neurobiological mechanisms controlling aggression: preclinical developments for pharmacotherapeutic interventions. Neurosci. Biobehav. Rev. 18:97–110.

Mills, A. D., and J. M. Faure, 1991. Divergent selection for duration of tonic immobility and social reinstatement behavior in Japanese quail (Coturnix coturnix japonica) chicks. J. Comp. Psychol. 105:25–38.

Moffitt, T. E., G. L. Brammer, A. Caspi, J. P. Fawcett, M. Raleigh, A. Yuwiler, and P. Silva, 1998. Whole blood serotonin relates to violence in an epidemiological study. Bio. Psychiatry 43:446–457.

Morello, H., L. Caligaris, B. Haymal, and S. Taleisnik, 1992. Daily variations in the sensitivity of proestrous LH surge in the inhibitory effect of intraventricular injection of 5-HT or GABA in rats. Can. J. Physiol. Pharmacol. 70:447–451.

Muir, W. M., 1996. Group selection for adaptation to multiple-hen cages: Selection program and direct responses. Poultry Sci. 75:447–458.

Muir, W. M., and J. V. Craig, 1998. Improving animal well-being through genetic selection. Poultry Sci. 77:1781–1788.

Nagatsuka, Y., 1983. The regulation of pituitary gonadotropin release of the frontal lobe neocortex. (II). In relation to serotonergic neurons. Nippon Naibunpi Gakkai Zasshi 59:1874–1883.

Naumenko, E. V., N. K. Popova, and L. N. Ivanova, 1987. Neuroendocrine and neurochemical mechanisms of the domestication of animals. Genetika 23:1011–1025.

Nestor, K. E., J. W. Anderson, and R. A. Patterson, 2000. Genetics of growth and reproduction in the turkey. 14. Changes in genetic parameters over thirty generations of selection for increased body weight. Poultry Sci. 79:445–452.

Olivier, B., R. van Oorschot, and M. D. Waldinger, 1998. Serotonin, serotonergic receptors, selective serotonin reuptake inhibitors and sexual behaviour. Int. Clin. Psychopharmacol. 13(Suppl. 6):S9–14.

Oquendo, M. A., and J. J. Mann, 2000. The biology of impulsivity and suicidality. Psychiatr. Clin. North. Am. 23:11–25.

Parmigiani, S., P. Palanza, J. Rogers, and P. F. Ferrari, 1999. Selection, evolution of behavior and animal models in behavioral neuroscience. Neurosci. Biobehav. Rev. 23:957–969.

Pietraszek, M. H., Y. Takada, D. Yan, T. Urano, K. Serizawa, and A. Takada, 1992. Relationship between serotonergic measures in periphery and the brain of mouse. Life Sci. 51:75–82.

Popova, N. K., N. N. Barykina, I. Z. Pliusnina, T. A. Alekhina, and V. G. Kolpakov, 1999. Manifestation of fear response in rats genetically predisposed to various kinds of defense behavior. Ross. Fiziol. Zh. Im. I M Sechenova. 85:99–104.

Popova, N. K., N. N. Kudriavtseva, and S. D. Lubsanova, 1978. Genetic control of the tissue concentration of serotonin in mice. Genetika 14:1804–1808.

Popova, N. K., A. V. Kulikov, D. F. Avgustinovich, N. N. Voitenko, and L. N. Trut, 1997. Effect of domestication of the silver fox on the main enzymes of serotonin metabolism and serotonin receptors. Genetika 33:370–374.

Popova, N. K., N. N. Voitenko, and L. N. Trut, 1975. Changes in the content of serotonin and 5-hydroxyindoleacetic acid in the brain during selection of silver foxes according to behavior. Dokl. Akad. Nauk. SSSR. 223:1498–1500.

Raleigh, M. J., M. T. McGuire, G. L. Brammer, D. B. Pollack, and A. Yuwiler, 1991. Serotonergic mechanisms promote dominance acquisition in adult male vervet monkeys. Brain Res. 559:181–190.

Richfield, E. K., A. B. Young, and J. B. Penney, 1987. Comparative distribution of dopamine D-1 and D-2 receptors in the basal ganglia of turtles, pigeons, rats, cats, and monkeys. J. Comp. Neurol. 262:446–463.

Savory C. J., and J. S. Mann, 1997. Is there a role for corticosterone in expression of abnormal behaviour in restricted-fed fowls? Physiol. Behav. 62:7–13.

Sharp, P. J., M. C. MacNamee, R. T. Talbot, R. J. Sterling, and T. R. Hall, 1984. Aspects of the neuroendocrine control of ovulation and broodiness in the domestic hen. J. Exp. Zool. 232:475–483.

Shea, M. M., L. W. Douglass, and J. A. Mench, 1991. The interaction of dominance status and supplemental tryptophan on aggression in Gallus domesticus males. Pharmacol. Biochem. Behav. 38:587–591.

Shea, M. M., J. A. Mench, and O. P. Thomas, 1990. The effect of dietary tryptophan on aggressive behavior in developing and mature broiler breeder males. Poultry Sci. 69:1664–1669.

Siegel, A., T. A. Roeling, T. R. Gregg, and M. R. Kruk, 1999. Neuropharmacology of brain-stimulation-evoked aggression. Neurosci. Biobehav. Rev. 23:359–389.

Siegel, H. S., 1995. Gordon Memorial Lecture. Stress, strains and resistance. Br. Poult. Sci. 36:3–22.

Siegel, H. S., and N. R. Gould, 1982. Corticosteroid binding to lymphocytes of various tissues in growth birds subjected to high temperatures. Gen. Comp. Endocrinol. 48:348–354.

Siegel, P. B., and E. A. Dunnington, 1997. Genetic selection strategies—population genetics. Poultry Sci. 76:1062–1065.

Sirotkin, A. V., and H. J. Schaeffer, 1997. Direct regulation of mammalian reproductive organs by serotonin and melatonin. J. Endocrinol. 154:1–5.

Sotowska-Brochocka, J., L. Martynska, and P. Licht, 1994. Dopaminergic inhibition of gonadotropic release in hibernating frogs, Rana temporaria. Gen. Comp. Endocrinol. 93:192–196.

Steklis, H. D., M. J. Raleigh, A. S. Kling, and K. Tachiki, 1986. Biochemical and hormonal correlates of dominance and social behavior in all-male groups of squirrel monkeys (Saimiri sciureus). Am. J. Primatol. 11:133–145.

Tecott, L. H., and S. H. Barondes, 1996. Genes and aggressiveness. Behavioral genetics. Curr. Biol. 6:238–240.

Thompson, D. L., K. D. Elgert, W. B. Gross, and P. B. Siegel, 1980. Cell-mediated immunity in Marek's disease virus-infected chickens genetically selected for high and low concentrations of plasma corticosterone. Am. J. Vet. Res. 41:91–96.

Tuomisto, J., and P. Mannisto, 1985. Neurotransmitter regulation of anterior pituitary hormones. Pharmacol. Rev. 37:249–332.

Unis, A. S., E. H. Cook, J. G. Vincent, D. K. Gjerde, B. D. Perry, C. Mason, and J. Mitchell, 1997. Platelet serotonin measures in adolescents with conduct disorder. Biol. Psychiatry 42:553–559.

Valzelli, L., 1984. Reflections on experimental and human pathology of aggression. Prog. Neuropsychopharmacol. Biol. Psychiatry 8:311–325.

Vogel, W. H., and N. Harris, 1991. Learning and memory of a water T-maze by rats selectively bred for low or high plasma catecholamine stress responses. Behav. Neural. Biol. 56:113–117.

Walker, E. A., T. Yamamoto, P. J. Hollingsworth, C. B. Smith, and J. H. Woods, 1991. Discriminative-stimulus effects of quipazine and 1-5-hydroxytryptophan in relation to serotonin binding sites in the pigeon. J. Pharamacol. Exp. Ther. 259:772–782.

Wilson, C. A., and A. J. Hunter, 1985. Progesterone stimulates sexual behaviour in female rats by increasing 5-HT activity on 5-HT2 receptors. Brain Res. 333:223–229.